The role of slope angle, ground roughness and stauchwall strength in the formation of glide-snow avalanches in forest gaps

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ABSTRACT: Mountain forests are a cost-efficient measure to prevent the release of glide-snow avalanches. However, avalanches still release in forest gaps. Well-tested silvicultural guidelines have been formulated to define the maximum gap dimensions. The guidelines are based on empirical observations and are valuable tools for forest managers. In this paper, we develop a physical model to describe the formation of glide-snow avalanches in forest clearings. Our goal is to place forest management guidelines on a better physical foundation which allows a more detailed examination of possible mitigation measures, including the role of dead-wood, surface modifications and underbrush. We model the snow cover as a two-dimensional visco-elastic continuum with a strain-rate dependent failure criterion. Avalanche release is hindered by basal friction at the snow-soil interface as well as the strength of the stauchwall located at the lower end of the release slab. The stauchwall resists the displacement of the gliding slab when melt-water reduces the basal friction. The stabilizing effects of trees are taken into account as they support the stauchwall. Our preliminary results reveal that for slope angles lower than $35°$ ground roughness prevents glide-snow avalanches from release; however, small trees and underbrush are often insufficient to prevent release in steep terrain. Our findings are consistent with the Swiss forest management guidelines for avalanche prevention. Not only the release area itself but also the stauchwall zone is crucial for glide-snow avalanche release. We discuss how the snow cover at the lower end of forest gaps could be supported through silvicultural management.

1. INTRODUCTION

Mountain forests play an important role in protecting the human environment against snow avalanches. Their primary function is to prevent *the release* of avalanches. Forests hinder the formation of weak layers in the snowpack; slab avalanche release is therefore improbable because of a highly fragmented stratification of the snow cover in forest areas (in der Gand, 1978; de Quervain, 1979; Salm, 1978; Imbeck, 1984; Gubler and Rychetnik, 1991). Furthermore, tree stems, underbrush and bushes support and stabilize the snow cover, preventing the formation of full-depth gliding avalanches (McClung, 1975; Salm, 1978; Imbeck, 1984; Newesely et al., 2000; Brang et al., 2006). Many studies indicate that in dense forest stands the formation of avalanches is unlikely (Imbeck and Meyer-Grass, 1988; Bebi et al., 2009; Teich et al., 2012). However, avalanches release in open forest structures, clearings or gaps (in der Gand, 1976; Imbeck, 1984; Zenke, 1989; Konetschny, 1990; Meyer-Grass and Schneebeli, 1992; Schneebeli and Bebi, 2004; Viglietti et al., 2010) (Fig. 1).

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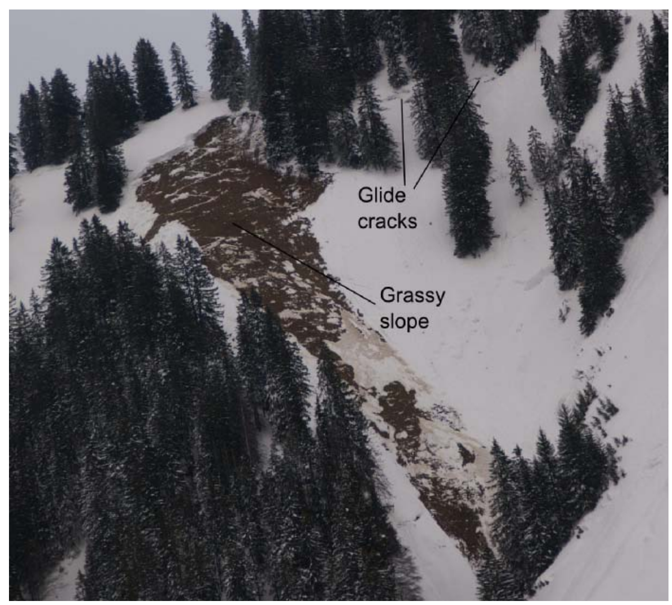

Figure 1: Glide avalanche in forest clearing. Characteristics are a smooth terrain (grass) and a slab length of approx. 100 m. Note the glide cracks in the smaller gaps without avalanches releasing.

Forest guidelines have been formulated that define allowable forest gap dimensions to ensure the prevention of destructive avalanches (Frehner et al., 2005). The guidelines are based on observations and statistical data analysis (Imbeck, 1984; Imbeck and Meyer-Grass, 1988; Meyer-Grass and Schneebeli, 1992). Probable avalanche release is related to clearing size and slope angle. The guidelines *qualitatively* consider ground roughness as an additional relevant factor, especially to prevent the release of full-depth gliding avalanches (In der Gand and Zupančič, 1966; McClung, 1975; Höller, 2004; Bartelt et al., 2012). However, many investigations have shown that ground roughness in forest clearings can differ significantly. For example, Höller (1997); Baier et al. (2007) and Höller et al. (2009) highlight the importance of dead debris or staged terrain to stop creep and glide of the snow cover and therefore protect young plants from being uprooted. Furthermore, a quantitative understanding of the influence of ground roughness on avalanche formation is relevant after natural disturbances (e.g. windthrow) or after management interventions (fostering of regeneration in protection forest management).

The capability of vegetation to increase the ground roughness and therefore prevent a gliding movement of the snow cover was studied by Salm (1978); de Quervain (1979); Fiebiger (1978); Newesely et al. (2000); Höller (2001) and Leitinger et al. (2008). All investigations show that glide snow avalanche activity is retarded by forest stands, situated at the lower edge of gaps. This area often corresponds to the stauchwall zone (Gubler and Rychetnik, 1991) (the fixed snow cover below gliding slabs) and its strength is crucial for glide snow avalanche release (Bartelt et al., 2012). The stauchwall zone, the lower end of the forest clearing, has scarcely been considered specifically in silvicultural management strategies.

To better understand the stabilizing effect of trees on the snow cover we employed a physical modeling approach based on the mechanical properties of the snow slab and the stauchwall (Bartelt et al., 2012). Typically a crack opens in the snow cover at the upper limit of the slab before an avalanche releases. However, a crack opening does not necessarily imply avalanche release which requires failure of the stauchwall. When the crack opens, the weight of the slab is transferred from the crown to the stauchwall leading to a visco-elastic stress redistribution (Bartelt et al., 2012). Basal roughness affects the stress redistribution and therefore plays an important role in failure and subsequent avalanche release. Weak basal snow layers, or layers lubricated by melt-water located at the soil-snow interface, thus play the deciding role for full-depth glide avalanche release in forests. In open terrain, the stauchwall is usually located at terrain steps, or regions with enhanced basal roughness, and therefore can transfer the slab load easily into the ground, thus preventing avalanche release. The identification of the exact location of the stauchwall is demanding (if not impossible) in open terrain as the properties of the basal interface are essentially unknown. In contrast to open terrain, as trees "fix" the snow cover to the ground, it is easier to define the location of the stauchwall and therefore the allowable length of the gap. We will exploit this relationship in this paper.

This short contribution proceeds in three steps. First we review observations of forest gap dimensions gathered between 1985 and 1990 in Switzerland. Then, we briefly present the two-dimensional tensile crack-slab-stauchwall model (Bartelt et al., 2012). We then calculate maximum forest gap lengths to prevent glide snow avalanche release. We assume a critical brittle strain rate for stauchwall failure (Scapozza and Bartelt, 2003). Forest gaps have a well defined length, width and lower boundary. This allows us to study the dependency on slope angle, ground roughness, snow density and characteristics of the stauchwall zone. Our purpose is to verify the model performance with the well-established guideline values.

2. Forest gap avalanche data

Between 1985 and 1990, 150 forest avalanches were documented in the Swiss Alps. The purpose of this large scale field study was to explore the role of forest stand characteristics on avalanche release. Snow characteristics (moisture content, snow height, snow cover stratification), avalanche type (wet, dry, glide snow), terrain characteristics (slope angle, curvature, exposition, surface roughness) and vegetation (type, height, density) were collected for each avalanche release zone; reference data was gathered immediately adjacent to the avalanche path, from regions that did not release, to determine which differences (forest structure, snow properties, ground characteristics) possibly led to failure.

From the total of 150 avalanches, 36 glide snow avalanche events could be clearly distinguished. We analyzed this refined data set to establish a relationship between the observed slope angle and ground properties on avalanche release in forest clearings (Fig. 2).

The comparison between the properties of the avalanche release zone and the ground properties of the adjacent (non-avalanche), control zone was particular helpful to demonstrate the importance of surface roughness. In 32 of the 36 case studies, the avalanche release was characterized as smooth /Fig. 2) (In comparison only 13 out of 22 of the adjacent, control regions were quantified as smooth.). In these case studies the slope angle of the avalanche release zone and the stable reference zone did not differ significantly (43 for avalanches, 42 for reference areas).

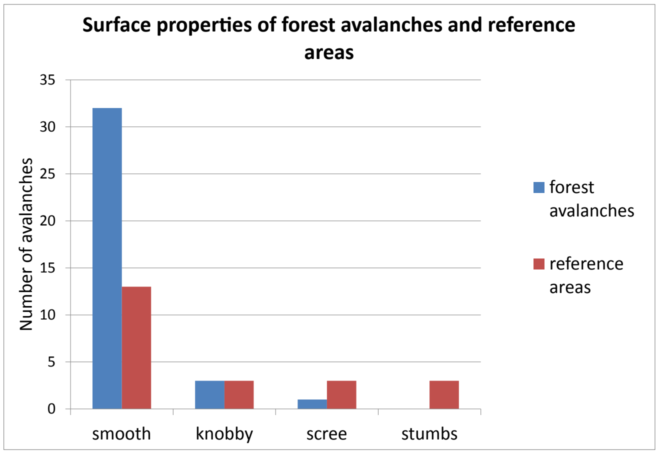

Figure 2: Comparison of surface properties of 36 glide snow avalanches and 22 reference areas in Switzerland.

3. MODELING

To predict avalanche release in forest gaps we apply the visco-elastic continuum model of Bartelt et al. (2012). This two-dimensional model was developed for open, non-forested slopes. The model divides the snow cover into two regions: the sliding zone and the stauchwall (Fig. 3). The sliding zone has length l; the stauchwall has length l_s and is fixed to the ground. We assume a snow cover with height h and a homogenous density ρ. Therefore, the total mass per unit area of the slab is $m = \rho l$. When a tensile crack opens, the tensile force at the crown is lost and must be transferred to the sliding zone and the stauchwall. It is possible that the lost force is balanced entirely by an increase in shear stress at the base of the snow cover. In this case no avalanche will release, but this scenario requires high friction to transfer the lost tensile force into the ground. Moreover, the driving force and the friction resistance are in balance:

$$mg_x = \mu m g_z; \tag{1}$$

where g_x and g_z are the gravitational accelerations in the slope parallel and normal directions, respectively. These depend on the slope angle α. When the interface balances the lost tensile force, it is seen as an increase in the friction μ. It is also possible that the lost force is taken up by the stauchwall. In this case there is an out-of-balance force σ that must be resisted by the stauchwall:

$$m\dot{u}(t) = mg_x - \mu m g_z - \sigma(t)h \tag{2}$$

where $u(t)$ is the displacement velocity of the slab. Because snow is a visco-elastic material, the stauchwall resisting stress σ is time dependent. A simple Burger's model is used to calculate the resisting action of the stauchwall:

$$\ddot{\sigma}(t) + \left[\frac{E_m}{\eta_m} + \frac{E_m}{\eta_k} + \frac{E_k}{\eta_k}\right]\dot{\sigma}(t) + \left[\frac{E_m E_k}{\eta_m \eta_k}\right]\sigma(t) = \frac{E_m}{2l_s}\dot{u}(t) + \frac{E_m E_k}{2\eta_k l_s}u(t). \tag{3}$$

The visco-elastic constants (E_m, E_k, η_m, η_k) are density and temperature dependent (Von Moos et al., 2003; Scapozza and Bartelt, 2003).

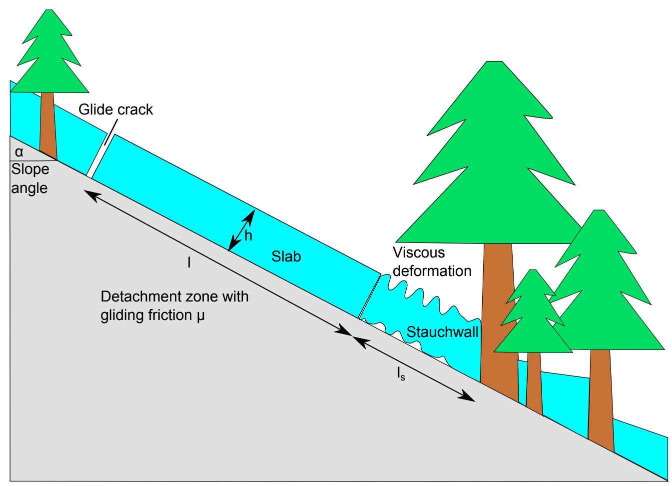

Figure 3: A two-dimensional visco-elastic continuum model is used to calculate the allowable gap length l. The model parameters are the slab length l, snow cover density ρ, stauchwall length l_s, surface roughness μ and slope angle α. Stauchwall failure is independent of the snow cover height h. Avalanche release is defined when the stauchwall collapses. A strain-rate dependent failure criterion is used.

Eqs. 2 and 3 are a system of two coupled ordinary differential equations that can be solved numerically. Numerical solutions are presented in Bartelt et al. (2012). The model predicts the total strain and strain-rates in the stauchwall, $\dot{u}/2l_s = \dot{\epsilon}$. When the strain-rates exceed a critical value, we consider the stauchwall to fail and an avalanche is released. A variation of the model is to assume that the slab consists of two regions (Fig. 4). In a slab region with length l_0

the shear resistance has almost been lost completely, for example by meltwater lubrication, μ = 0. In the remaining slab region of length l_μ the frictional resistance has not been lost. In this preliminary study we did not consider this second, and perhaps more realistic case.

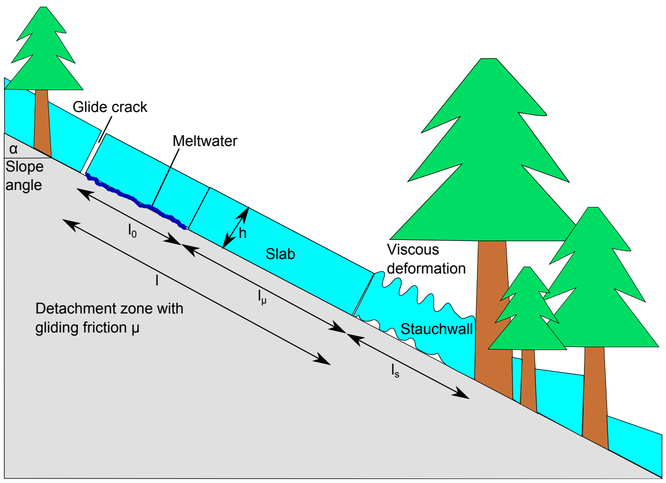

Figure 4: The slab can be divided into an upper part (l_0, $\mu = 0$) and a lower part (l_μ, $\mu \neq 0$), see Bartelt et al. (2012). The region l_0 has no friction, as in the extreme case when meltwater lubricates a portion of the sliding surface.

To apply the model in forests, the length l defines the forest spacing. Consequently we define the location of the stauchwall right above the first trees of the lower boundary (Fig. 3). These trees physically act to fix the snow cover to the ground.

4. RESULTS

We applied the model in a series of calculations with the goal to highlight the importance of surface roughness on full-depth avalanche release and to determine the allowable gap length. We calculated for a given slope angle and slab length, the basal friction at failure. We term this friction the "critical" basal friction, but it physically represents the surface roughness, the sliding zone *must have* (for a given slope angle and slab length) to ensure stability. This critical friction is physically related to surface properties, underbrush, terrain steps or mitigation measures. Thus, high critical friction values require higher levels of mitigation, for example, technical measures. If the critical friction is low, then perhaps simple silvicultural measures like plantings are sufficient.

Failure is defined when the stauchwall is overcome (Bartelt et al., 2012). This requires the complete compressive collapse of the snow in the stauchwall. We parameterize failure using a critical strain-rate, determined in triaxial snow tests by Von Moos et al. (2003) and Scapozza and Bartelt (2003). In these tests compressive collapse was preceded by shear failure; thus, we implicitly assume a shear band develops in the stauchwall at failure. Snow above the shear plane is removed as the slab slides over the shear plane. We set this failure strain rate to $\dot{\epsilon}$ = 0.01, as found by Von Moos et al. (2003) and Scapozza and Bartelt (2003). The density range of the triaxial tests corresponds well with the snow cover densities encountered in forests, between 200 kg/m^3 and 400 kg/m^3. For the preliminary investigations we set the density to ρ = 250 kg/m^3. The viscoelastic constitutive parameters of the model correspond to this density (E_m = 1.5e^8 Pa, E_k = 1.5e^7 Pa, η_m = 1.4e^9 Pa s, η_k = 2.5e^6 Pa s, see Von Moos et al. (2003)).

We investigated gap lengths l between 30 m and 60 m in 10 m intervals; we also varied the slope angle α from 30° to 45° in 5° steps. Thus, we performed 16 base calculations, but for each calculation we had to iterate the friction value μ to determine the critical friction. The friction μ was changed in steps of $\Delta\mu$ = 0.01. This defines the accuracy of the critical friction values. It was not necessary to change the height of the snow cover as we always assumed that the snow cover and stauchwall had the same height (see Bartelt et al. (2012)). Clearly variations in snow cover depth will play an important role; however, we did not investigate this effect in this study. We set the stauchwall length to l_s = 5 m corresponding to the effective stress zone influenced by the trees.

The results of our calculations are depicted in Fig. 5 showing the critical friction values as a function of slab length and slope angle. Higher slope angles and longer slab lengths require higher ground roughness to prevent stauchwall failure. The relationships are linear and the friction value varies by 0.05 for 10 m slab length and 0.1 for each 5° increase in slope angle.

If we assume a specific roughness, μ = 0.45, then we have a good agreement with the empirical guideline values. Thus, the guidelines implicitly assume a particular surface roughness corresponding to μ = 0.45. This helps to relate μ to "typical" or "mean" surface features of forest clearings that can be at least intuitively defined by forest managers. Also note, that for a slab length of less than 70 m the friction coefficient μ remains below 0.5 for slope angles below 35°. Steep forest clearings (greater than 35°) with long gaps (l $\geq$ 70 m) therefore require intensive mitigation measures to produce higher surface roughness.

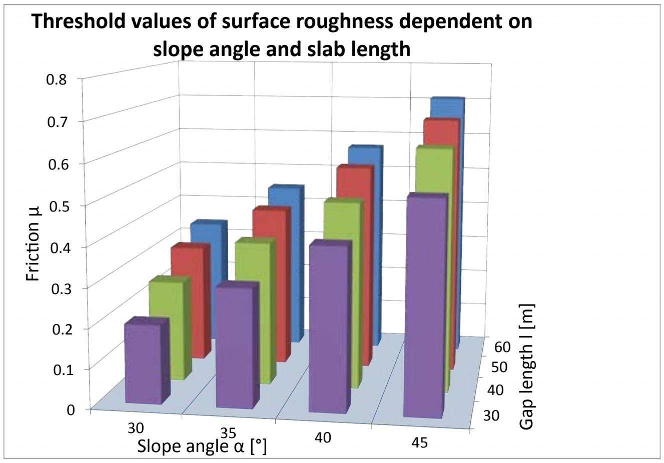

Figure 5: The critical friction parameter values μ dependent on slab length l and slope angle α for a stauchwall length l_s = 5 m, snow cover density ρ = 250 kg/m^3 and a critical strain rate $\dot{\epsilon}$ = 0.01 1/s.

In a second series of calculations we varied the density of the snow cover. We found that a higher density snow cover (ρ = 350 kg/m^3) shifted the critical friction upwards by 0.05. Thus, heavier snow-packs (in warmer climates, or in later winter) decrease the allowable gap length. This increase in critical friction ($\Delta\mu$ = 0.05) translates into a Δl = 10 m reduction in allowable length.

5. CONCLUSIONS AND OUTLOOK

We developed a simple analytical model that relates slab length, basal friction and slope angle to the strength properties of the stauchwall. The fundamental assumption of the model is that when a glide crack opens there is an immediate transfer of stress from the crown to the ground (via basal friction) and stauchwall. Failure depends on the strength properties of the snow as well as the friction at the basal interface. The length of the slab defines the magnitude of the stress transfer and therefore the loading rate on the stauchwall. With this model we can reproduce the empirical, observation based, Swiss guidelines for allowable dimensions of forest gaps. We find that the guidelines implicitly assume a reasonable, but generic friction value. With the model we could quantify this surface friction value to be μ = 0.45. Future studies are needed to underpin this value. This will require field studies of avalanches where the release dimensions as well as the surface properties are quantified in detail. Above all, we need to determine the friction values for both technical measures, for example terrain steps or ground-log spacings, and natural obstacles, such as young trees, dead wood and underbrush.

The model also assumes that the surface properties are static; that is, they do not change as a function of time. This is clearly not the case with the production of melt-water in the snow cover, which will cause the basal friction to decrease significantly. Thus, we find the guidelines are based on static values that do not account for time-dependent processes such as temperature variations. It is possible in the next step to include zones of melt-water lubrication and to investigate how the extent of melt-water zones influences the allowable gap lengths (Fig. 4). This would enable forest managers to treat forest gaps with different expositions and elevations according to different hazard scenarios.

A particularly important result is that we can quantify the relationship between basal friction and slope angle. At high slope angles, the allowable length decreases, but also the critical friction increases, indicating when technical measures become necessary. This suggests that the model can be used to determine the required spacing of full-depth technical measures which are similar to the forest boundaries in that they fix the snow cover and transfer the load to the ground. Above each defense structure is a stauchwall. The results also indicate that any method which can support the stauchwall region, such as densify the vegetation cover at the lower edge of the clearing, could be a cost-efficient strategy for forest-avalanche mitigation. However, for this one cannot safely rely on model results and therefore real one-to-one experiments in controlled conditions would be helpful.

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